(54) Title: ENDOSCOPIC IMAGING PROBE COMPRISING DUAL CLAD FIBRE
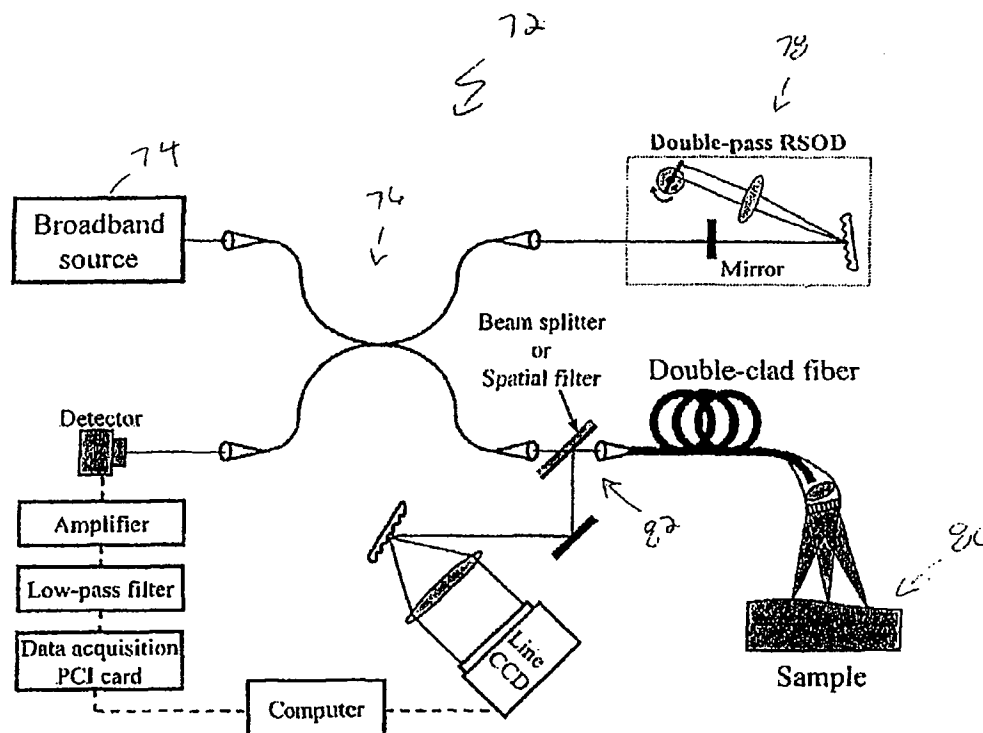
(57) Abstract: A method and a related apparatus for optical imaging in particular for performing three-dimensional surface measurements. The apparatus comprises a double-clad or a multi-clad fibre. Several varieties of transmitting the light through the fibre to the sample and collecting the light reflected from the sample in the fibre are disclosed.

ENDOSCOPIC IMAGING PROBE COMPRISING DUAL CLAD FIBRE

FIELD OF THE INVENTION

[0001] This invention relates generally optical imaging and more particularly to a method and apparatus for performing three-dimensional surface measurements.

BACKGROUND OF THE INVENTION

[0002] As is known in the art, fiber optic endoscopy is typically conducted by transmitting an image through an array of fibers often referred to as a fiber bundle. While successful for a variety of medical and non-medical applications, utilization of an array of fibers to form the image imposes constraints on the cost, diameter, and flexibility of the imaging device.

[0003] In an attempt to overcome these drawbacks, multiple approaches employing a single optical fiber have been proposed for miniature, flexible endoscopes. For example, one technique for confocal imaging with a single fiber has been implemented by utilizing the core of a single-mode fiber as both the source and the detection apertures. Also, miniature confocal microscope probes and endoscopes have been constructed by adding a mechanical micro-scanner at the tip of a single-mode fiber. Another single-fiber method for miniature endoscopy, termed spectral encoding, uses a broadband light source and a diffraction grating to spectrally encode reflectance across a transverse line within the sample as described in Tearney et al. Opt. Lett. 27: 412 (2002). A two-dimensional image is formed by slowly scanning this spectrally encoded line and a three-dimensional image may be obtained by placing the probe in the sample arm of an interferometer as described in Yelin et al. Opt. Lett. 28: 2321 (2003). The core of the single-mode fiber acts as both the source and the detection apertures for all of these techniques.

[0004] As is also known, one important design parameter for single-fiber endoscopy is the modal profile of the optical fiber. Single-mode optical fibers enable high resolution imaging with small and flexible imaging probes, but suffer from relatively poor light throughput. Furthermore, the small core of the single-mode fiber acts similarly to a pinhole in free-space confocal microscopy, preventing the detection of

out-of-focus light. For endoscopic applications, this optical sectioning may not be desirable since a large depth of field, large working distance, and wide field of view are typically preferred. For endoscopic microscopy applications, optical sectioning may be sacrificed for increased light throughput.

[0005] When illuminated by coherent sources, imaging via single-mode fibers also introduces so-called speckle noise, which significantly reduces the effective resolution and quality of the images. Replacing the single-mode fiber with a relatively large diameter multi-mode optical fiber enables higher optical throughput and decreases speckle. Unfortunately, utilization of a large diameter multi-mode fiber severely deteriorates the system's point-spread function and prevents the use of interferometry for high sensitivity and three-dimensional detection.

[0006] Recently, significant progress has been made developing high power fiber lasers utilizing double-clad (also called 'dual-clad') optical fibers. These fibers are unique in their ability to support single mode propagation through the core with multi-mode propagation through the inner cladding.

SUMMARY OF THE INVENTION

[0007] In accordance with the present invention, a method for imaging a sample through an optical fiber having a core and at least one cladding region includes (a) transmitting a first propagating mode of light through the core of the optical fiber toward the sample and (b) collecting scattered light from the sample in at least a first one of the at least one cladding regions of the optical fiber. Using the fiber's core for illumination and the inner clad for signal collection reduces image speckle, improves depth of field and increases signal efficiency (i.e. allows the collection of more light). Fiber core for illumination and inner clad for signal collection increases depth of field because an increase in the diameter of the collection aperture increases the depth of field and increased diameter of collection aperture increases the amount of light that can be detected through that aperture. This of course assumes that the collection aperture diameter of the inner cladding is greater than that of the core. A modeling of this effect is represented in FIGs. 3B and 3C below

[008]   In accordance with a further aspect of the present invention, a method for imaging a sample through an optical fiber having a core and at least one cladding region includes (a)transmitting a first propagating mode of light through at least one of the at least one cladding regions toward the sample and (b) collecting scattered light from the sample in a core of the optical fiber. With this particular arrangement, a technique in which inner cladding of a double clad fiber (or multi-clad fiber) can be used to deliver the illumination light, and the core can be used to collect the light. The large, high numerical aperture (NA), inner clad allows for efficient coupling of illumination light that is spatially incoherent from light sources such as Halogen, Mercury or Xenon lamps. This approach maintains the reduced image speckle due to the multiple illumination angles and the large depth of field, at the expense of a subtle drop in image resolution. The signal collection efficiency is lower compared to the core-illumination clad-collection scheme discussed above, but the increase in excitation light can compensate for that by increasing the signal.

[009]   In accordance with a further aspect of the present invention, a system for imaging a sample includes a light source for transmitting a first propagating mode of light through a core of a double-clad optical fiber toward the sample and collecting scattered light from the sample in at least a first cladding region of the double-clad optical fiber. In some embodiments, it may be desirable to collect light in both the cladding region and the core of the fiber.

[0010] With this particular arrangement, an imaging system which utilizes the core of a fiber for illumination and the inner clad of the fiber for signal collection is provided. This results in a technique which reduces image speckle and provides improved depth of field and increased signal efficiency. Using the fiber's core for illumination and the inner clad for signal collection reduces image speckle, improves depth of field and increases signal efficiency. It should, however, be appreciated that the double-clad fiber can be used by taking the opposite approach: the inner clad can be used to deliver the illumination light, and the core to collect the light. The large, high numerical aperture (NA), inner clad allows for efficient coupling of illumination light that is spatially incoherent from light sources. This approach maintains the reduced image speckle due to the multiple illumination angles and the

large depth of field, at the expense of a subtle drop in image resolution. The signal collection efficiency is lower compared to the core-illumination clad-collection scheme discussed earlier, but the increase in excitation light can compensate for that by increasing the signal. In some embodiments, it may be advantageous to process information collected through both the core and the cladding regions regardless of whether the illumination light, is delivered through the core or the cladding. By separately collecting information through both the core and the cladding, information provided from one source (e.g. thought the core) can be used to enhance the information collected from the other (e.g. through the cladding). The information collected through each channel (e.g. the core-transmit / core-collection channel, the core-transmit / cladding-collection channel) can be processed and combined to provide information concerning the sample which is not readily available or apparent from the information collected in any single channel. Since the light returned through the core has higher transverse spatial frequencies than light collected through the cladding, one example of such combination of core and cladding light would be to utilize the information obtained through the core to sharpen the information received through the cladding. Additionally, light detected from the core is single mode which enables three-dimensional or phase sensitive information to be obtained when used in conjunction with an interferometer. This information can be utilized to enhance the incoherent information received by the inner cladding in the form of an overlay or pseudocolor representation of phase or three-dimensional information superimposed onto the spatially incoherent information provided by light detected through the inner cladding.

[0011] Similarly, information collected through a cladding-transmit / core-collection channel and a cladding-transmit / cladding-collection channel can be processed and combined to provide information concerning the sample which is not readily available or apparent from the information collected in any single channel. In one example of such processing, image information collected by the core can be utilized to sharpen image information received by the inner cladding.

[0012] In summary, the use of a double-clad optical fiber in an imaging system provides many benefits to single optical fiber based imaging. In addition to improved

image quality, utilization of a double clad fiber enables implementation of single mode illumination with both single- and multi-mode detection, by incorporating a detection beam-splitter with spatial filtering. This enhancement can enable dual-mode imaging where the multi-mode detection can be used to obtain the diffuse endoscopy image and the single-mode detection could be used for interferometric detection such as that employed by three-dimensional spectrally-encoded endoscopy.

[0013] It has been found that double-clad optical fiber can be used to obtain speckle-free, signal-efficient spectrally-encoded imaging. By coupling the illuminating broadband light into the fiber's core only, and collecting the reflected light with the inner cladding (a configuration which is referred to herein as single mode-multimode or SM-MM), it is possible to combine the benefits of single-mode illumination with the advantages of multi-mode signal collection.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The foregoing features of this invention, as well as the invention itself, may be more fully understood from the following description of the drawings in which:

[0015] FIG. 1A is a block diagram of an optical system for spectrally-encoded imaging with a double-clad fiber;

[0016] FIG. 1B is an expanded cross-sectional view of the double-clad fiber of FIG. 1;

[0017] FIG. 2A is a photograph of a standard white light image of a face of a doll;

[0018] FIG. 2B is an image of the face of the doll of FIG. 2A generated using spectrally-encoded imaging with single-mode illumination and single-mode collection (SM-SM);

[0019] FIG. 2C is an image of the face of the doll of FIG. 2A generated using spectrally-encoded imaging with single-mode illumination and multi-mode collection

(SM-MM);

[0020]   FIG. 2D is an image of the face of the doll of FIG. 2A generated using spectrally-encoded imaging with multi-mode illumination and multi-mode collection (MM-MM);

[0021]   FIG. 3A is a block diagram of a system for signal collection using a double-clad fiber (DCF) in which a lens images scattered light onto the face of an inner clad layer;

[0022]   FIG. 3B is a plot of normalized SM-MM transverse (solid line) and axial spot sizes, plotted as a function of inner cladding diameter;

[0023]   FIG. 3C is a plot of speckle contrast and normalized total signal intensity;

[0024]   FIG. 4A is a block diagram of a signal collection system which illustrates using a double-clad fiber in which a lens images scattered light onto the face of an inner clad layer of the fiber;

[0025]   FIG. 4B is a block diagram of a signal collection system using a double-clad fiber in which a lens images scattered light onto the face of a core of the fiber;

[0026]   FIG. 5A. is a block diagram of a system which utilizes a double-clad fiber for both coherent light collection (collection of light through the core only) and non-coherent light collection (light collection through the inner clad only); and

[0027]   FIGs. 6A-6E are a series of cross-sectional views of probes which utilize a double clad fiber.

DETAILED DESCRIPTION OF THE INVENTION

[0028]   Referring now to Fig. 1, an optical system 10 for spectrally-encoded imaging with a double-clad fiber includes a broadband light source 12 which transmits light to a beam splitter (BS) 14. A first portion of the light is directed toward a double clad

fiber (DCF) 16. The light propagates through the DCF 16 and through a collimating lens 18 to a miniature imaging probe 19.

[0029] In FIG. 1, the miniature imaging probe 19 is simulated using a compact lens grating design provided from a lens 20 and a grating 22. A galvanometric optical scanner 24 controlled by a processor 34 to performs slow axis scanning. The scanner directs the light toward a surface of a sample 25.

[0030] Light scattered from the sample 25 is coupled into the inner cladding or core or both the inner cladding and core of the DCF 16 and deflected by the beam splitter 14 (BS) to a spectrometer 29. In this exemplary embodiment, spectrometer 29 includes a lens 28, a diffraction grating 30, and a high-speed line-scan camera 32. The images can then be provided to a computer 34 or other processing system where the images can be displayed and stored.

[0031] In one embodiment, the light source 12 may be provided as a broadband light source such as a KLM Ti:Al$_2$O$_3$ laser (750-950nm) and coupled to the core of the double-clad fiber 16 using an NA=0.4 microscope objective lens. The double-clad fiber 16 may be provided as the type available through Fibercore Limited having a 3.7 μm core diameter (4.1 μm mode-field diameter), NA=0.19, and a 90 μm diameter cladding, NA=0.23 and identified as a SUMM900. The light transmitted from the core of the DCF 16 was collimated using an NA=0.4 microscope objective lens 18 to approximately a 2 mm beam diameter.

[0032] Imaging using single mode detection and collection (denoted as SM-SM) was accomplished by replacing the double-clad fiber (i.e. DCF 16 in FIG. 1) and the beam splitter (i.e. BS 14 in Fig. 1) with a single-mode 50/50 fiber-splitter (e.g. a single-mode 50/50 fiber-splitter of the type provided by Gould Electronics Inc., Corning HI 780-5/125 fiber, NA=0.14). In one embodiment, the miniature imaging probe was simulated by using a compact lens-grating design in which the beam was first focused by the lens 20 (L1, f = 65 mm) and then diffracted by the transmission grating 22 (G1, 1000 lines/mm) to form a line on the surface of the sample. In another embodiment, the miniature imaging probe comprises a DCF with an

objective lens such as a gradient index lens (GRIN) attached to the distal end of the DCF. In another embodiment, a spacer and angled grating is affixed to the distal end of a GRIN lens attached to the DCF. In yet a further embodiment, the probe is comprised of a DCF, lens, dual-prism GRISM and objective lens, as is described in Pitris C, Bouma BE, Shishkov M, Tearney GJ. A GRISM-based probe for spectrally encoded confocal microscopy. Optics Express 2003; 11:120-24.

[0033]   The lens 28 (L2) can be provided having f=40 mm, the diffraction grating 30 (G2) can be provided having 1200 lines/mm, and the camera 32 can be provided as a high-speed line-scan camera such as a Basler L104k. With these components, the power on the sample was 2 mW.

[0034]   To demonstrate spectrally-encoded imaging with the double-clad fiber, the face of a small doll was imaged using three different fiber-based illumination-detection configurations. The results of these three different fiber-based illumination-detection configurations are shown and described below in conjunction with FIGs. 2B-2D.

[0035]   Referring now to Fig. 2A, an image of a doll's face obtained using white light illumination and a CCD camera is shown. The scale bar (in the lower right hand corner of FIG. 2A) represents 2 mm. This image is presented for comparison with the images shown in FIGS. 2B – 2D.

[0036]   FIG. 2B is an image of the doll's face obtained with single-mode illumination and single-mode detection (denoted SM-SM).

[0037]   FIG. 2C is an image of the doll's face obtained with single-mode illumination and multi-mode detection (denoted as SM-MM).

[0038]   FIG. 2D is an image of the doll's face obtained using multi-mode illumination with multi-mode detection (MM-MM) where the excitation light was coupled mainly to the inner cladding.

[0039] The SM-SM image (FIG. 2B) had relatively high resolution and contrast, but was corrupted by speckle noise. While the SM-MM image (Fig. 2C) had slightly lower resolution compared with the SM-SM image, its appearance was more natural and more similar to the white light reference image (Fig. 2A). Also, due to an increase in depth of field, the doll's neck and the shoulder could be seen in the SM-MM image, whereas the small core diameter of the SM-SM image rejected the signal coming from these regions.

[0040] The MM-MM image (Fig. 2D) did not contain speckle noise and had the largest depth of field, but also had a dramatically reduced resolution compared to the resolution of the SM-SM or SM-MM images. The images that utilized multi-mode collection, FIGs. 2C and 2D, were also much brighter than the SM-SM image.

[0041] In order to gain better understanding of the underlying process that lead to these results, various imaging parameters, including the transverse and axial resolution, collected signal intensity, and speckle contrast were numerically simulated for different inner cladding diameters and experimentally measured for the SM-SM and SM-MM configurations.

[0042] Referring now to FIG. 3A, the signal collection geometry of a double-clad fiber 41, used for the numerical simulations is shown. The grating G1 and the galvanometric scanner shown in FIG. 1 were omitted from this illustration for simplicity and to maintain the generality of the scheme. The spatially coherent light (dashed rays 42) emanated from the core 44 and was focused to a small spot on the rough surface 46a of the sample 46. It was assumed that the light from the sample surface 46a scattered equally in all directions. By imaging the diffused light spot resultant from illuminating a variety of samples e.g. paper, razor blade and a volunteer's finger, it was found that the area covered by the diffused light extended to a typical size of about 200 mm. The scattered light 50 (dotted lines) was imaged back onto the face of the fiber, and coupled mainly into the inner cladding 52.

[0043] For point-spread function calculations, the double-clad fiber 41 was treated as a confocal imaging system, where the inner cladding 54 was simulated by a finite-

sized pinhole, thereby establishing a correspondence between results obtained with the above-described system and previously published confocal microscopy calculations. Due to the discrete nature of the number of propagating modes in the inner cladding 54, the validity of this approximation depends upon the specific fiber parameters. For example, for an NA = 0.23 cladding, a 6 μm diameter fiber supports 13 propagation modes at a wavelength of 0.85 μm. This number increases proportionally to the cladding area, and as a result, for our 90 μm diameter inner cladding, one would expect nearly 3000 modes to be guided. Since a large number of modes are guided by the inner cladding of the SMM900, the pinhole model is expected to correspond to experimental measurements for this double-clad fiber.

[0044] Referring now to FIG. 3B, by numerically solving the Fresnel integral, the full width at half maximum (FWHM) of the point-spread function was calculated. The transverse and the axial spot sizes, normalized to unity when the cladding diameter was equal to the core diameter, are shown as solid and dashed lines, respectively, in Fig. 3B. The transverse spot size increased by up to a factor of 1.4 and then remained constant for large cladding diameters, while the axial spot increases almost linearly. The transverse point-spread function was measured by taking the derivative of the signal from an edge in an air-force resolution chart. The full width at half maximum (FWHM) of the measured point-spread function was 17.4 ± 1.5 μm using the SM-SM configuration (the mean of 35 locations on the image), and 27.7 ± 2.9 μm for the SM-MM case (shown by a filled circle in Fig. 3B). The FWHM of the measured signal, obtained by scanning a mirror along the optical axis through the focal point, was measured for the SM-SM and SM-MM configurations to be about 2.1 ± 0.3 mm and 18.5 ± 3 mm, respectively. The ratio between these measurements was 8.8, which was slightly lower than the ratio of 10.5 obtained from our simulation.

[0045] Efficient signal collection is important for high signal-to-noise ratio imaging. The detected signal intensity was calculated by simulating 1000 rough surfaces (one random surface for each point on the sample) with uniformly distributed random amplitude and phase, within a Gaussian intensity envelope of 200 μm.

[0046] Referring now to FIG. 3C, a plot of normalized total signal intensity that was

collected with the inner cladding is shown as a dashed line. It should be appreciated that all SM-MM values are normalized to those of the SM-SM case and that the error bars represent one standard deviation. For small cladding diameters, the signal collection increased with the cladding area. The total collected signal reached a plateau as the cladding covered the entire extent of the scattered light. The total signal from a highly scattering paper at the object plane was measured and it was found that the signal collected with the SMM900 inner cladding was 32.5 times stronger than the signal that was collected in the SM-SM case (diamonds in FIG. 3C). This measurement was in good agreement with the ratio of 35 obtained from a simulation.

[0047] Speckle noise is one of the limiting factors in many coherent imaging techniques. It reduces the effective resolution, produces image artifacts and makes images look unnatural. Using the simulation described above for the detected signal intensity, speckle noise was calculated by dividing the standard deviation of the image by its mean. The resulting speckle contrast, plotted as a solid line in FIG 3C, rapidly decreases with the increasing cladding diameter. The speckle contrast for 50 lines of an image of a rough aluminum surface was measured. For the SM-SM configuration the speckle contrast was found to be 0.76 ± 0.09 and for the SM-MM case, a speckle contrast was found to be 0.1 ± 0.15 (shown in filled circles on the plot), corresponding to a reduction of speckle by a factor of 7.6. This ratio was in good agreement with that of a simulation, which demonstrated a ratio of 9.4.

[0048] These experiments and simulations show the benefits of the SM-MM configuration for single-fiber endoscopy. As expected, when the diameter of the inner cladding was equal to the diameter of the core (SM-SM), the results demonstrated coherent or confocal behavior. The images in this case had the highest resolution and contrast, but suffered from speckle noise, low signal power and a relatively limited depth of field. The SM-MM configuration provided by the double clad fiber is analogous to opening the pinhole in a free space confocal microscope. The large area of the cladding improved the detection efficiency, increased the depth of field, and decreased speckle noise, resulting with natural-appearing endoscopy images.

[0049] Choosing the optimal clad diameter depends upon the requirements of the specific application. Clad diameters around 10-20 µm, that are only slightly larger than the core diameter, would reduce speckle and increase the signal with only minor reduction in both transverse and depth resolution. Such a configuration is desired in confocal endoscopic imaging, for example, rejection of out of focus light is used to obtain optical sectioning. When optical sectioning is not necessary, or when large depth of field is required, large clad diameters can be used, as was demonstrated in the work described above.

[0050] Double-clad optical fibers can be used to enhance several other fiber-based imaging and non-imaging systems, in particular, systems that do not need coherent signal detection and would benefit from the increase in signal and in depth of field, such as fluorescence and Raman fiber probes.

[0051] Referring now to FIG. 4A, a system 60 for fluorescence or Raman signal collection using a double-clad fiber probe is shown. Light 61 emanates from a core 62 of a double-clad fiber 64 and is directed through a lens 66 toward a surface 68a of a sample 68. Light 69 reflects of the sample 68 back through the lens 66 and onto the face of the fiber, and coupled mainly into the inner cladding 70 of the fiber 64.

[0052] Referring now to FIG. 4B, a system 60' for fluorescence or Raman signal collection using a double-clad fiber probe is shown. Light 61 emanates from a cladding region 70' of a double-clad fiber 64' and is directed through a lens 66' toward a surface 68a of a sample 68. Light 69' reflects off the sample 68 back through the lens 66' and onto the face of the fiber, and coupled mainly into the core 62' of the fiber 64'.

[0053] Thus, the double-clad fiber can be used by taking an approach opposite to that described in FIG. 4A. Specifically, as shown in FIG. 4B, the inner clad can be used to deliver the illumination light, and the core to collect the light. The large, high NA, inner clad allows for efficient coupling of illumination light that is spatially incoherent from light sources such as Halogen, Mercury or Xenon lamps. This

approach maintains the reduced image speckle due to the multiple illumination angles and the large depth of field, at the expense of a subtle drop in image resolution. The signal collection efficiency is lower compared to the core-illumination clad-collection scheme discussed earlier, but the increase in excitation light can compensate for that by increasing the signal.

[0054]   Referring now to FIG. 5A, a system 72 which uses double-clad fiber (DCF) to perform both coherent and non-coherent light collection (i.e. coherent collection of light through the core only and non-coherent collection of light through the inner clad only) includes a broadband light source 74 which transmits light through a fiber coupler 76 having a first port coupled to a double-pass Rapid Scanning Optical Delay (RSOD) line and a second port coupled to a double-clad fiber (DCF) 78. Light propagates through the DCF to a sample 80. The coherent light is transmitted through the core and coupled back into a fiber splitter 82. An interference pattern between this light and the light from the delay line at the reference arm can be detected by a single detector (as shown in the figure), or by a charge coupled device (CCD) array or by using any other technique and apparatus now known or later discovered.

[0055]   It should be noted that when the DCF is used for fluorescence detection, there is no need to utilize a coherent detection scheme since the fluorescence light is not coherent. In addition to conventional fluorescence and reflectance, other imaging modalities may benefit from collection of the remitted light by a second cladding of the fiber, including second harmonic, third harmonic, two-photon fluorescence, Raman scattering, coherent-anti-stokes Raman (CARS), surface-enhanced-Raman scattering (SERS) and the like.

[0056]   It should be appreciated that the benefits provided by the double-clad fiber, namely the reduced speckle, the improved depth of field and the increase in signal collection efficiency, can be obtained with different fiber or waveguide designs. It should this be appreciated that any configuration in which the sample is illuminated with a beam that provides a resolution spot that is acceptable by the imaging system, and the light collection is performed by a larger aperture in the fiber, may provide similar benefits.

[0057]   FIGs 6A-6E are a series of cross-sectional views which illustrate several possible probe designs.

[0058]   Referring now to FIG. 6A, a probe can be provided as a double clad fiber having a core 90, a first cladding layer 92 and a second cladding layer 94.

[0059]   Referring now to FIG. 6B, a probe can be provided as a multi-clad fiber having a core 96 and a plurality of cladding regions 98a – 98c.

[0060]   Referring now to FIG. 6C, a double clad fiber having a core 100 and a cladding 102 with an arbitrary cladding shape is shown. It should be appreciated that while this particular embodiment is shown as a double clad fiber, a multi-clad fiber may also be provided a cladding layer having an arbitrary shape.

[0061]   Referring now to FIG. 6D, a probe comprises a single-mode fiber 104 and a multimode fiber.

[0062]   Referring now to FIG. 6E, a probe includes a core 108 and a plurality of a single-mode fibers 110a – 110f for illumination and multi mode waveguides as shown in FIG. 6E for signal collection disposed about the core 108.

[0063]   It should be understood that in addition to all of the benefits provided by the probe and fiber configurations described above, coherence detection can still be performed by a single-mode illuminating core, or any other single mode waveguide in the probe. Coherence detection may provide depth sensitivity and allow for use of a heterodyne detection scheme to allow for weak signal detection.

[0064]   Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. For example, as discussed above, using the fiber's core for illumination and the inner clad for signal collection

reduces image speckle, improves depth of field and increases signal efficiency. It should, however, be appreciated that the double-clad fiber can be used by taking the opposite approach: the inner clad can be used to deliver the illumination light, and the core to collect the light. The large, high NA, inner clad allows for efficient coupling of illumination light that is spatially incoherent from light sources such as Halogen, Mercury or Xenon lamps. This approach maintains the reduced image speckle due to the multiple illumination angles and the large depth of field, at the expense of a subtle drop in image resolution. The signal collection efficiency is lower compared to the core-illumination clad-collection scheme discussed earlier, but the increase in excitation light can compensate for that by increasing the signal.

[0065] Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. It should further be noted that any patents, applications and publications referred to herein are incorporated by reference in their entirety.

What is claimed is:

CLAIMS

1   1.   A method for imaging a sample through an optical fiber having a core and at
2   least one cladding region, the method comprising:
3   (a)   transmitting a first propagating light through the core of the optical fiber
4   toward the sample; and
5   (b)   collecting scattered light from the sample in at least a first one of the at least
6   one cladding regions of the optical fiber.

1   2.   The method of claim 1 wherein the optical fiber is provided having a plurality
2   of cladding regions and the method further comprises collecting scattered light from
3   the sample in more than one of the plurality of cladding regions of the optical fiber.

1   3.   The method of claim 2 further comprising collecting scattered light from the
2   sample in each of the cladding regions of the optical fiber.

1   4.   The method of claim 1 further comprising collecting scattered light from the
2   sample in the core of the optical fiber.

1   5.   The method of claim 3 wherein the optical fiber is provided having a plurality
2   of cladding regions and the method further comprises collecting scattered light from
3   the sample in more than one of the cladding regions of the optical fiber.

1   6.   The method of claim 1 wherein transmitting a first propagating mode of light
2   through the core of the optical fiber toward the sample comprises:
3   transmitting spatially coherent light through the core of the fiber.
4   focusing the spatially coherent light onto a spot on a surface of a sample; and
5   collecting, in an inner cladding region of the fiber, light scattered from the
6   sample surface.

1   7.   The method of claim 6 wherein transmitting a first propagating mode of light
2   through the core of the optical fiber toward the sample further comprises focusing the
3   spatially coherent light onto a spot on a surface of a sample

1   8.   A method for imaging a sample through an optical fiber having a core and at

2   least one cladding region, the method comprising:

3   (a)   transmitting a first propagating mode of light through at least one of the at

4   least one cladding regions toward the sample; and

5   (b)   collecting scattered light from the sample in a core of the optical fiber.

1   9.   The method of claim 8 wherein the optical fiber is provided having a plurality

2   of cladding regions and the method further comprises collecting scattered light from

3   the sample in each of the cladding regions of the optical fiber.

1   10.   A probe comprising:

2   a light transmission path provided as one of an optical fiber and an optical

3   waveguide, with the light transmission path provided having a light transmission

4   aperture through which light propagates to illuminates the sample with a beam of

5   light having a desired resolution spot,; and

6   a light collection path which is separate from the light transmission path, said

7   light collection path having an aperture which is larger than the aperture of the light

8   transmission aperture.

1   11.   The probe of claim 9 wherein:

2   the light transmission path corresponds to a first one of a fiber core and a

3   fiber cladding region; and

4   the light collection path corresponds to a second different one of a fiber core

5   and a fiber cladding region.

1   12.   The probe of claim 11 wherein the light collection path is provide from both a

2   fiber core and a fiber cladding region.

1   13.   The probe of claim 11 wherein the probe is comprised of one of:

2   (a) a double-clad fiber;

3   (b) a multi-clad fiber;

4   (c) one single-mode and one multimode fiber;

5 (d) a single-mode fiber for illumination and one or more multi mode waveguides for

6 signal collection;

7 (e)   a plurality of a single-mode fibers for illumination and one or more multi-mode

8 waveguides for signal collection.

1 14.   The probe of claim 11 wherein the probes is provided having an irregularly

2 shaped cladding layer.

1 15.   The probe of claim 14 further comprising coherence detection means

2 coupled to the probe to receive signals from at least one of:

3   the single-mode illuminating core; and

4   the single mode waveguide in the probe

5 such that coherence detection can be performed.

1 16.   An optical system 10 for spectrally-encoded imaging with a double-clad fiber

2 comprising:

3   a light source 12;

4   a beam splitter (BS) 14 disposed to intercept light transmitted by said light

5 source;

6   a double clad fiber (DCF) 16 disposed to intercept light directed thereto by

7 said beam splitter and to allow light to propagate along the light transmission path

8 thereof; and

9   a collimating lens 18 disposed to intercept light from said double clad fiber;

.0 and

.1   an imaging probe disposed to receive light directed thereto from said

.2 collimating lens and including a light transmission path to direct light toward the

.3 sample and a light collection path to receive light reflected from the sample.

1 17.   The system of claim 16 wherein:

2   said light source is provided as a broadband light source; and

3   said imaging probe is provided as a miniature imaging probe.

1 18.   The system of claim 17 wherein:

2   said light source transmits a first propagating mode of spatially coherent light

3   toward the sample through one of: a core of the optical fiber or a cladding region of

4   the optical fiber;

5   said imaging probe focuses the spatially coherent light onto a spot on a

6   surface of a sample;

7   said imaging probe transmits light toward the sample in one of:

8   a cladding region of a fiber;

9   a core region of the fiber; and

.0   said imaging probe collects light reflected from the sample in one of:

.1   a cladding region of fiber;

.2   a core region of the fiber.

.3

1   19.   The system of claim 17 wherein:

2   said light source is provided as a broadband light source; and

3   said imaging probe is provided as a miniature imaging probe.

1/7
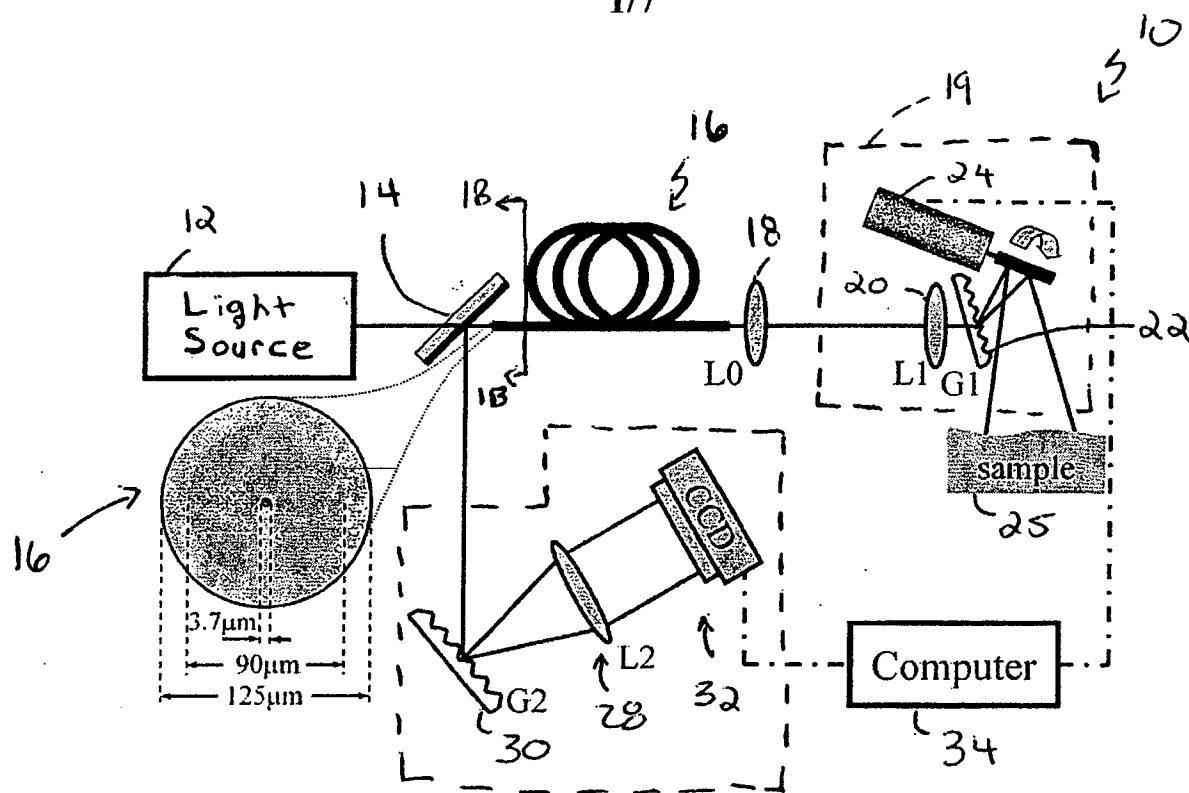
FIG. 1B

FIG. 1A

FIG. 2A   FIG. 2B
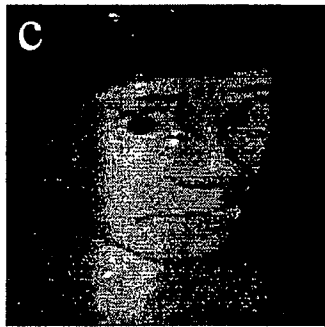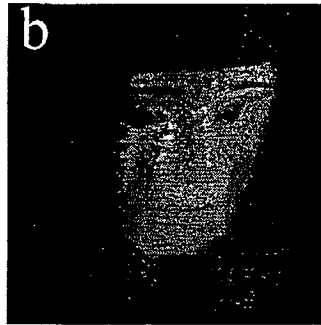
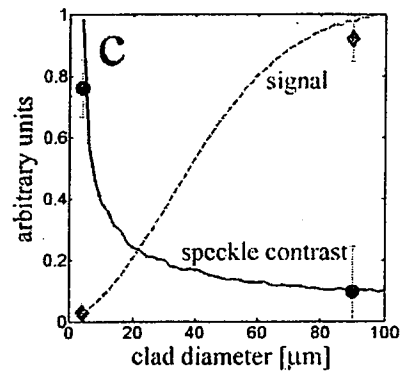
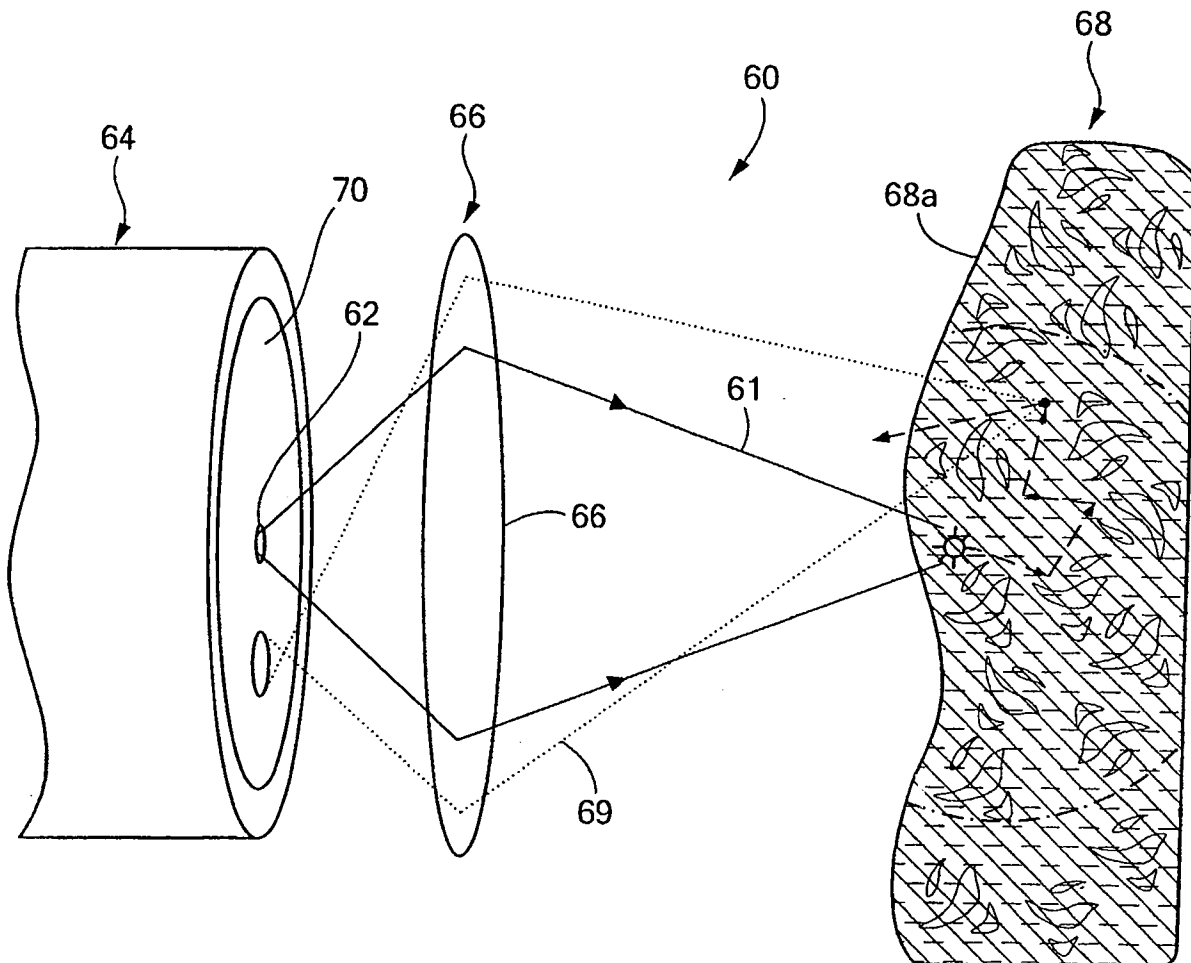FIG. 2C   FIG. 2D
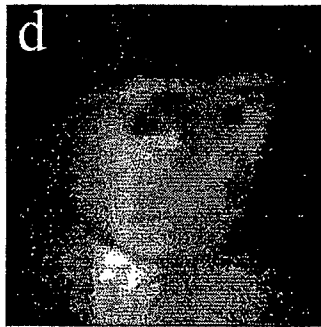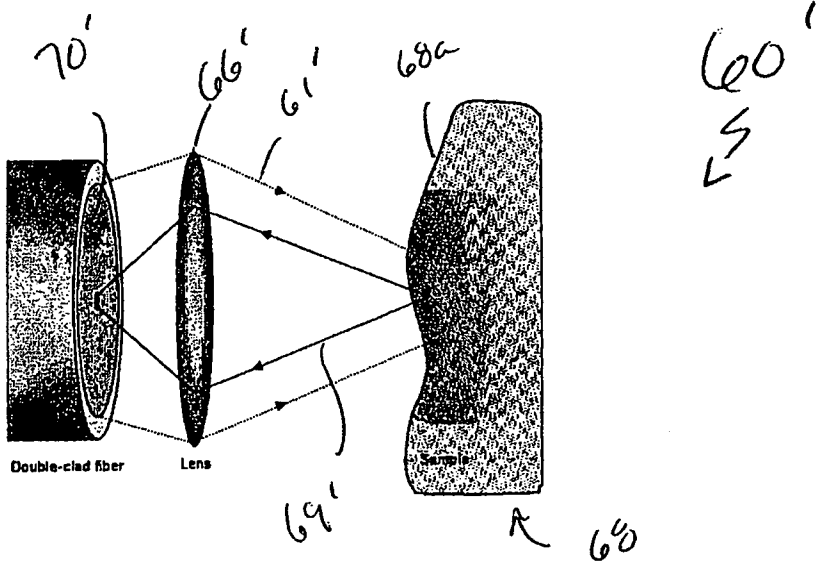
FIG. 3A
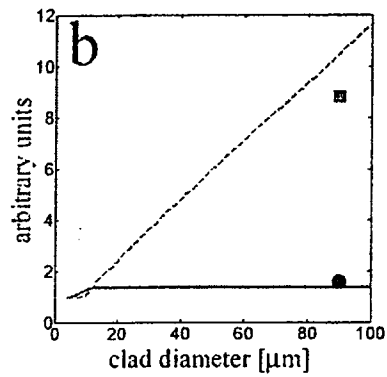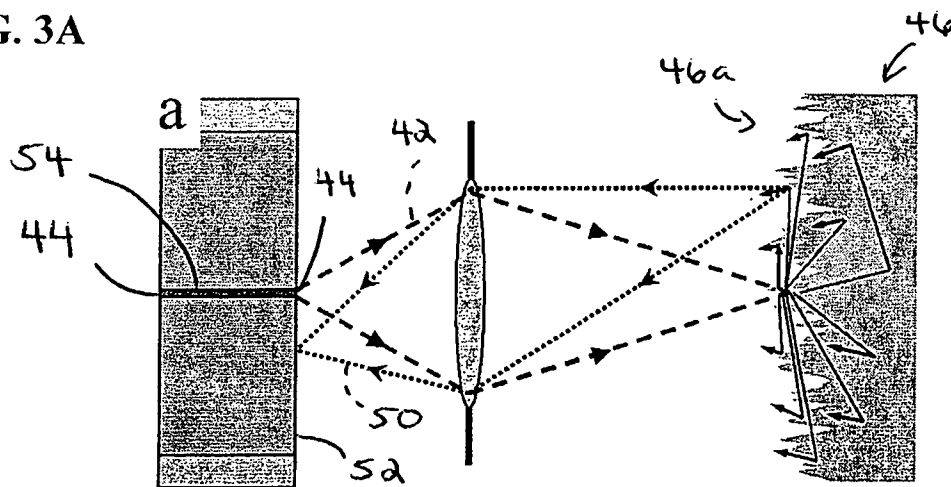
FIG. 3B   **FIG. 3C**

FIG. 4A

FIG. 4B
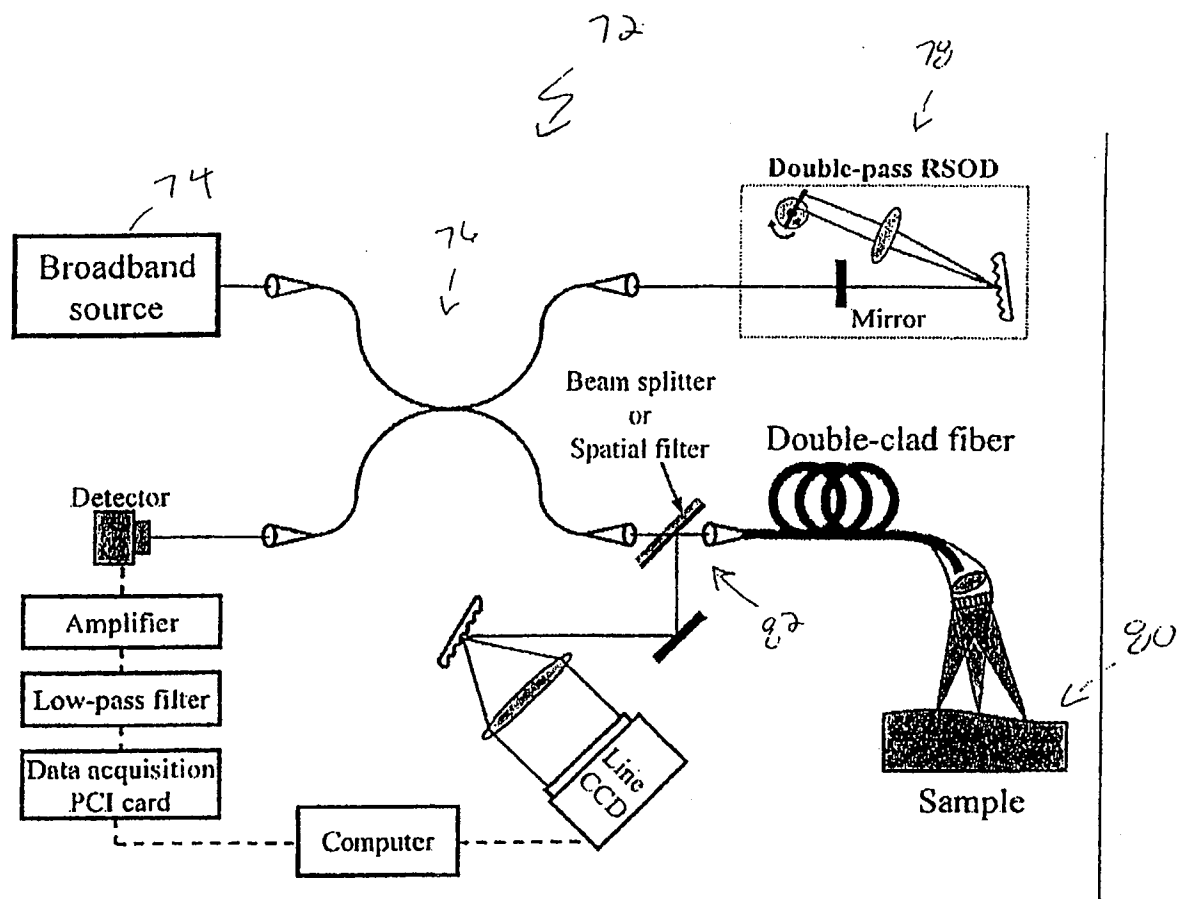
FIG. 5 A

FIG. 6A
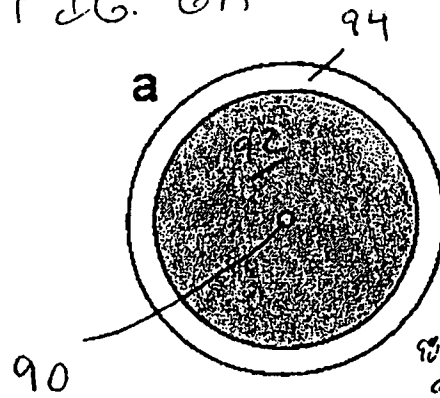
FIG. 6B
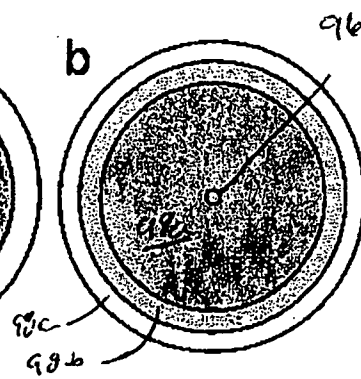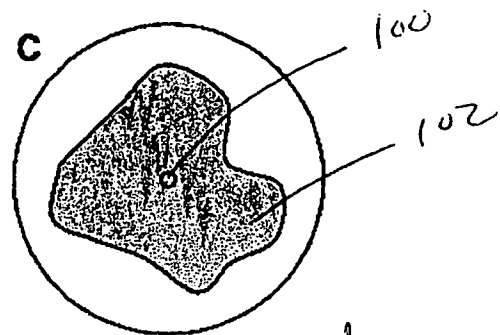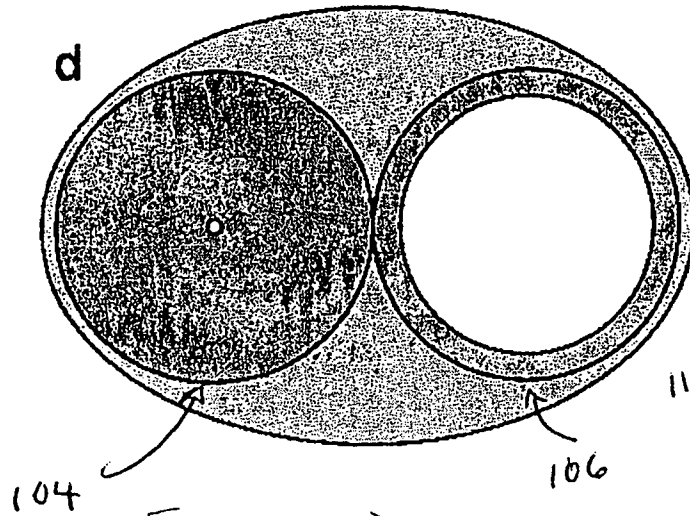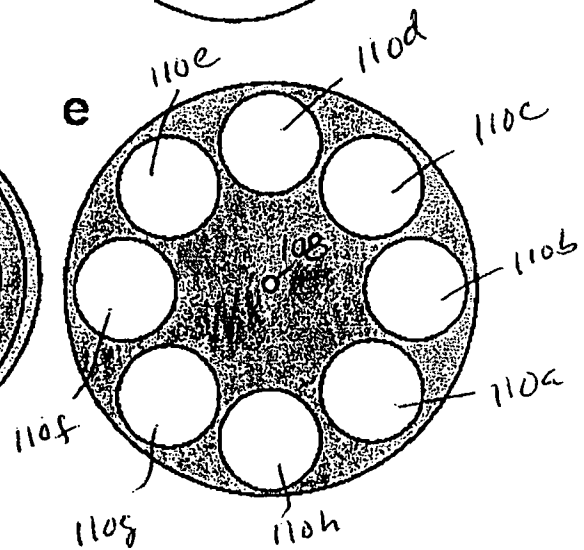
FIG. 6C

FIG. 6D

FIG. 6E

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G02B6/036   G01B9/04   G01B11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G02B   G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 02/38040 A (THE GENERAL HOSPITAL CORPORATION; TEARNEY, GUILLERMO, J; BOUMA, BRETT,) 16 May 2002 (2002-05-16) page 7 - page 8; figures 1,2	1,4,6,7, 10-13, 16-19
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A	abstract; figures 1,4-6	15
X	DE 195 42 955 A1 (HERBERT SCHWIND GMBH & CO KG, 63801 KLEINOSTHEIM, DE; POLYDIAGNOST VER) 22 May 1997 (1997-05-22) figure 5	10,13

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| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

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Date of the actual completion of the international search	Date of mailing of the international search report
29 September 2005	12/10/2005

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Beutter, M

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P,A	YELIN D ET AL: "Double-clad fiber for endoscopy" OPTICS LETTERS OPT. SOC. AMERICA USA, vol. 29, no. 20, 15 October 2004 (2004-10-15), pages 2408-2410, XP002347219 ISSN: 0146-9592 the whole document	1-19
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A	US 4 770 492 A (LEVIN ET AL) 13 September 1988 (1988-09-13) abstract; figure 1B	10

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